Biomass and Carbon Partitioning in Switchgrass

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ABSTRACT

Grasslands have an underground biomass component that serves as a carbon (C) storage sink. Switchgrass (*Panicum virgatum* L.) has potential as a biofuel crop. Our objectives were to determine biomass and C partitioning in aboveground and belowground plant components and changes in soil organic C in switchgrass. Cultivars Sunburst and Dacotah were field grown over 3 yr at Mandan, ND. Aboveground biomass was sampled and separated into leaves, stems, senesced, and litter biomass. Root biomass to 1.1-m depth and soil organic C to 0.9-m depth was determined. Soil C loss from respiratory processes was determined by measuring CO_2 flux from early May to late October. At seed ripe harvest, stem biomass accounted for 46% of total aboveground biomass, leaves 7%, senesced plant parts 43%, and litter 4%. Excluding crowns, root biomass averaged 27% of the total plant biomass and 84% when crown tissue was included with root biomass. Carbon partitioning among aboveground, crown, and root biomass showed that crown tissue contained approximately 50% of the total biomass C. Regression analysis indicated that soil organic C to 0.9-m depth increased at the rate of 1.01 kg C m^{-2} yr^{-1}. Carbon lost through soil respiration processes was equal to 44% of the C content of the total plant biomass. Although an amount equal to nearly half of the C captured in plant biomass during a year is lost through soil respiration, these results suggest that northern Great Plains switchgrass plantings have potential for storing a significant quantity of soil C.

The rapid rate of increase in atmospheric CO_2 levels has placed emphasis on better understanding the role of agriculture in mitigating this increase. The vast area of perennial grasslands and the large C-laden root biomass associated with grasslands suggests that grassland agriculture can contribute to reducing atmospheric CO_2 concentrations. Native grasslands contain large amounts of soil organic C mainly because of their large root biomass (Frank et al., 1995). Measurement of CO_2 fluxes have shown grasslands are generally a net sink for atmospheric CO_2 (Frank and Dugas, 2001; Frank et al., 2000; Sims and Bradford, 2001; Suyker and Verma, 2001). Some suggest native grasslands are at soil organic C equilibrium and that expecting significant increases in soil C would not be feasible (Cole, 1996; Parton et al., 1987). However, tilled soils are often degraded to levels of soil organic C significantly lower than before tillage. Reseeding tilled soils with perennial grasses has been shown to provide greater litter and root biomass for C storage than an annual cereal crop (Mapfumo et al., 2002). Mensah et al. (2003) found that restored grasslands gained about 0.7 Mg C ha^{-1} yr^{-1}.

Switchgrass is a perennial grass species that is being proposed as a biofuels crop to help mitigate the atmospheric CO_2 gain resulting from increases in anthropogenic activities (Zan et al., 1997). Switchgrass has many traits that make it an attractive crop for sequestration of atmospheric CO_2. It has an extensive deep root system, about 50% greater water-use efficiency than cool season forage grasses (Ma et al., 2000a; Stout et al., 1988), a relatively low nutrient requirement (Hetrick et al., 1988), and the potential to produce large amounts of biomass (Sladden et al., 1991; Bransby et al., 1998).

The extensive root system in switchgrass is a trait that is beneficial for increasing soil C storage. Zan et al. (1997) showed that switchgrass produced more root biomass than corn (*Zea mays* L.). Increases in soil C under switchgrass were not present 3 yr after seeding, but at 10 yr, soil C was 45% greater at the 0- to 0.15-m depth and 28% greater at the 0.15- to 0.3-m depth. Garten and Wullschleger (2000) found that 5 yr after establishment, 19 to 31% of the soil C pool originated from switchgrass. Although switchgrass has many traits that make it a desirable biofuel crop, the benefits for C sequestration and soil C storage are not fully known. The level of C uptake and soil C gain in switchgrass stands will be influenced by the level of prior soil C loss from tillage, soil type, cultivars, nutrient status, and precipitation (Ma et al., 2000b; Zan et al., 1997; Bransby et al., 1998; Garten and Wullschleger, 2000). However, Bransby et al. (1998) suggested switchgrass is more important as a biofuel crop than for C sequestration. They also suggested replacement of annual crops with switchgrass is not economical and that using switchgrass to replace established pastures would not result in greater C sequestration.

The objectives of this study were to determine biomass and C partitioning in aboveground and belowground plant components and changes in soil organic C for two switchgrass cultivars. The cultivars Sunburst and Dacotah were field grown on two soil types over 3 yr near Mandan, ND. The carbon balance data presented in this report are simply a function of biomass yields with no regard for energy inputs from fertilizer or mechanical practices.

MATERIALS AND METHODS

The two sites (south and north) were located about 4 km apart at the Northern Great Plains Research Laboratory, Mandan, ND (latitude 46°46′ N, longitude 100°55′ W). The soil at the south site is a Werner-Sen-Chama complex (loamy, mixed, superactive, frigid shallow Entic Haplustoll; fine-silty, mixed, superactive, frigid Typic Haplustoll; fine-silty, mixed, superactive, frigid Typic Calciustoll) and at the north site is Parshall fine sandy loam (coarse-loamy, mixed, superactive, frigid

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Abbreviations: C, carbon; N, nitrogen; LAI, leaf area index.

Pachic Haplustolls). Before this study the sites were fallowed for 2 yr and before that were used as germplasm nurseries for cool-season grasses.

A duplicate set of plots of cultivars Dacotah and Sunburst were included in a switchgrass evaluation trial that was seeded 27 May 1999 at the north site and 28 May 1999 at the south site. The second set of plots was used in this study, each plot consisting of 10 rows spaced 0.36 m apart and 6 m long. All other plots were used for cultivar evaluation. Seeding rate was approximately 132 pure live seeds per m of row. Atrazine (6-chloro-*N*-ethyl-*N*′-isopropyl-1,3,5-triazinediyl-2,4-diamine) was applied immediately after seeding at 2.25 kg a.i. ha^{-1}. Plots were fertilized at 67 kg N ha^{-1} and 56 kg P ha^{-1} in October of 1999. Thereafter, plots were fertilized with 67 kg N ha^{-1} in October of each year. Nitrogen source was ammonium nitrate (34–0–0) and P was ammoniated phosphate (11–48–0). The aboveground biomass of each plot was machine harvested in mid-October of the establishment year and thereafter on approximately 15 September each year to a stubble height of approximately 0.15 m. The area surrounding the field plots and all alleyways was seeded to four rows of cultivar Fleet meadow bromegrass (*Bromus riparius* Rehm.) spaced 0.36 m apart. The two cultivars used in this study were randomized within each of four replicates in a randomized complete block design.

Plant biomass was measured by clipping two rows at soil level to provide a 0.25 m^2 area in each of four replicates with initial clippings on 15 May 2000, 8 May 2001, and 22 May 2002, and the final clippings on 13 Sept. 2000, 4 Sept. 2001, and 17 Sept. 2002. A total of eight clippings were made each year at approximately 15 to 21 d intervals from separate areas within each plot for each clipping over the 3-yr period. Leaves were manually separated from stems and leaf area was measured with a belt-driven photoelectric area meter. Green leaves, green stems, and senesced material were oven dried at 70°C for 72 h and weighed to obtain total aboveground live and dead biomass. Detached senesced biomass or litter was gathered from the clipped area dried and weighed. Seed heads were included in the stem samples.

Root biomass was measured on 24 July 2000, 17 July 2001, and 25 July 2002 by removing three 66-mm diameter soil cores directly over the seeded row to 1.1-m depth per replication. Each core was cut into segments of 0- to 0.1-, 0.1- to 0.2-, 0.2- to 0.3-, 0.3- to 0.6-, 0.6- to 0.9-, and 0.9- to 1.1-m depth increments. Plant crown material was separated from the root biomass and processed the same as the root biomass. Crown biomass was the material left after clipping off all stem and root tissue. The three cores were composited to make a single sample. Roots were washed, oven-dried, and weighed. All live and dead roots were included in the sample.

All aboveground and belowground plant tissue components were ground twice to pass a 0.64-mm screen with a shear-type mill. Tissue C content was determined by dry combustion with a Carlo Erba model NA1500 automatic C-N analyzer (Hake Buckler Instruments, Inc., Saddle Brook, NJ). Root samples in increments below 0.1 m were combined into a single sample to provide sufficient material for analysis.

Soil organic C and total nitrogen contents were measured by removing three 32-mm diameter cores from the mid point between rows in each replicate to 0.9 m depth on 24 July 2000, 17 July 2001, and 25 July 2002. Each core was cut into segments of 0- to 0.05-, 0.05- to 0.1-, 0.1- to 0.2-, 0.2- to 0.3-, 0.3- to 0.6-, and 0.6- to 0.9-m depth increments. The three cores were composited for each depth increment and processed by removing all visible root material. Subsamples of approximately 140 g oven dried soil were removed for determining soil bulk density and water content. The remainder of each sample was oven dried at 31°C for 72 h, crushed to pass a 2-mm sieve, ground to 200 μm, and stored in glass bottles. Total soil C content was determined by dry combustion using the aforementioned C–N analyzer as described by Schepers et al. (1989). A separate subsample of approximately 3 g oven dried soil was acidified to determine inorganic soil C content (Loeppert and Suarez, 1996), which was subtracted from the total soil C content to obtain total organic C. Loss of soil C was estimated from soil CO_2 flux measurements between approximately 1300 and 1500 h every 15 to 21 d from 2 May to 11 Oct. 2000, from 9 May to 15 Nov. 2001, and from 29 Mar. to 4 Nov. 2002 using a closed system consisting of a 1259-cm^3 soil chamber with a 95-mm diameter opening, a model 6262 infrared gas analyzer, and a model 670 gas flow control unit (LI-COR, Lincoln, NE). One ring per replication (polyvinyl chloride 104-mm-inside diameter by 50 mm deep) was placed about 25 mm in the soil approximately 2 wk before the first measurement. The soil surface within the rings was kept free of any live vegetation and residue. Daily rates of soil C loss were scaled to the measurement period of 1 May to 17 October assuming losses were similar during measurement intervals. Prior work has shown that soil C loss is mainly a function of soil temperature and that changes in soil temperature over a 24-h period in a grassland stand with complete canopy cover are small. Frank et al. (2002) showed that soil CO_2 flux measurements made during the 1300- to1500-h period was representative of daily flux rates.

Statistical analysis was conducted by SAS PROC MIXED with repeated measures (Littell et al., 1996). The primary objectives of this study were to determine biomass and C partitioning in switchgrass. All measurements were made on the same field sites over a 3-yr period and over eight dates for each year. Two covariance models were used to fit the repeated measures to evaluate the effects of cultivar, year, and date on biomass. A comprehensive model, which included both repeated measures effects, year, and date, was fit using an unstructured@compound symmetry direct product structure. A separate model which focused on entry and year effects across sampling dates used the unstructured covariance structure for the single repeated measures factor, year. All analyses considered cultivars, years, and dates as fixed effects and sites as random effects. Means were obtained with the lsmeans statement. Significance among cultivars, dates, years, and interactions were tested by appropriate *F*-ratios and mean differences were compared using Tukey's test. Throughout this paper date effects are not of major interest; thus, date interactions will not be discussed.

RESULTS AND DISCUSSION

Annual precipitation at a weather station approximately 0.5 km from the north site was 554 mm in 2000,

Table 1. Tests of statistical significance for biomass components for Dacotah and Sunburst switchgrass sampled on eight dates in 2000, 2001, and 2002. Root and crown biomass were sampled on a single date each year.

Source	Total	Stems	Leaves	Senesced	Litter	LAI	Roots	Crowns
Cultivar	**	**	**	NS	NS	**	NS	NS
Year	**	**	**	**	**	**	**	NS
Cultivar × year	**	**	**	NS	NS	**	NS	NS
Date	**	**	**	**	**	**		
Cultivar × date	**	**	**	NS	NS	**		
Year × date	**	**	**	**	**	**		
Cultivar × year × date	**	**	**	**	NS	**		

** Significant at $P = 0.01$.
NS, nonsignificant.

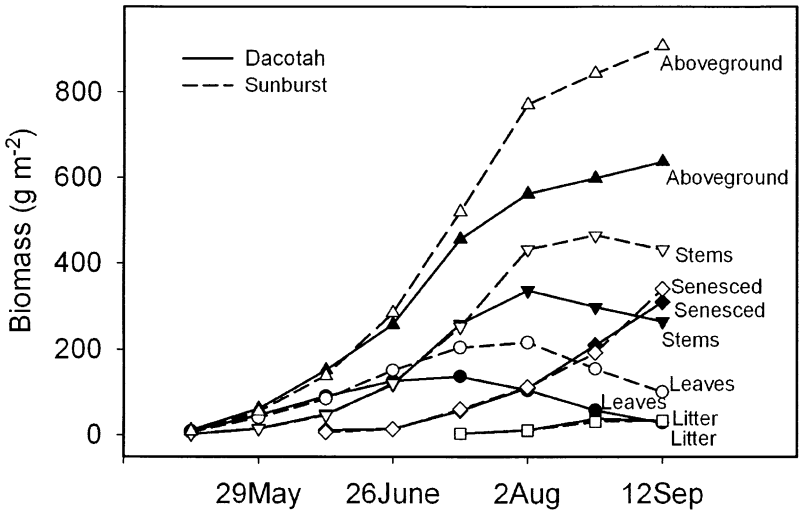

Fig. 1. Changes in biomass of leaves, stems, senesced leaves and stems, litter, and total biomass for Dacotah and Sunburst switchgrass on eight sample dates averaged over 2000, 2001, and 2002. Some tests for significance are presented in Table 1.

501 mm in 2001, and 292 mm in 2002. Precipitation exceeded the long-term average by 27% in 2000 and 19% in 2001, but in 2002 only 72% of the long-term average was received. The long-term annual precipitation at Mandan is 404 mm with 21% of the annual precipitation occurring in June.

Rate of morphological development of Dacotah was more rapid than Sunburst. Dacotah matured about 3 to 4 wk earlier and headed about 21 d earlier than Sunburst in 2000 and 2001. In the drought year of 2002, Dacotah headed about 35 d earlier than Sunburst. Both cultivars produced seven leaves except in the drought year of 2002 when Dacotah had five leaves and Sunburst six leaves. At time of flag leaf formation Sunburst averaged five to six green leaves and Dacotah averaged three to four green leaves. After flag leaf formation the rate of increase in leaf senescence was similar for both cultivars.

There were differences among cultivars and/or years for total aboveground biomass and for biomass partitioned into stems, leaves, LAI, litter, crowns, senesced, and root biomass and their interactions with sampling date (Table 1). The partitioning of biomass among leaves and stems reflects differences in maturity and total biomass production of the two cultivars (Fig. 1). Total biomass production averaged 42% more for Sunburst (908 g m^{-2} yr^{-1}) than for Dacotah (637 g m^{-2} yr^{-1}). The most rapid rate in total biomass increase occurred from 12 June sampling to heading stages on 12 July for Dacotah and on 2 August for Sunburst. Following heading, total biomass increased slightly. Stems accounted for more biomass in both cultivars after the 12 July sampling than any other plant component. Overall, stems accounted for 56% of Sunburst total aboveground biomass on the 12 July sampling compared to 60% for Dacotah, but at the final harvest Sunburst stems made up 48% of total biomass compared to 42% for Dacotah. Leaf biomass peaked on the 12 July sampling for Dacotah and on the 2 Aug. sampling for Sunburst. Leaf biomass was 19% of Dacotah biomass on 12 July compared to 28% for Sunburst. At the final harvest, leaf biomass

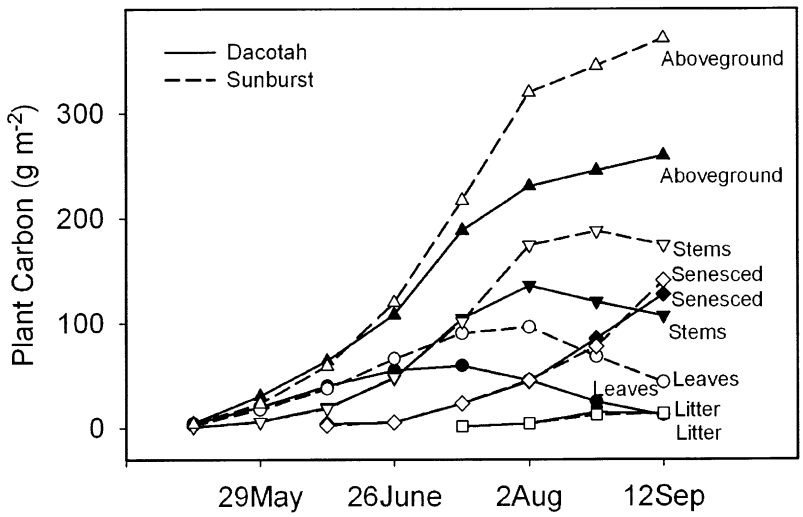

Fig. 2. Changes in C content in leaves, stems, senesced leaves and stems, litter, and total biomass for Dacotah and Sunburst switchgrass on eight sample dates averaged over 2000, 2001, and 2002. Some tests for significance are presented in Table 2.

Table 2. Tests of significance for C content in biomass components for Dacotah and Sunburst switchgrass sampled on eight dates in 2000, 2001, and 2002. Roots and crowns were sampled on one date each year.

Source	Stems	Leaves	Senesced	Litter	Roots	Crowns
Cultivar	**	**	NS	NS	NS	NS
Year	**	**	**	**	**	**
Cultivar × year	**	**	NS	NS	NS	NS
Date	**	**	**	**		
Cultivar × date	**	**	NS	NS		
Year × date	**	**	**	**		
Cultivar × year × date	**	**	**	NS		

** Significant at $P = 0.01$.
NS, nonsignificant.

was reduced to 11% for Sunburst and 4% for Dacotah. Senesced biomass increased from 19% for Dacotah and 14% for Sunburst on the 12 July sampling date to 49% for Dacotah and 37% for Sunburst at final harvest. Litter biomass was a small part of the total biomass and was similar for both cultivars. Overall, the biomass partitioning on any date reflected the rate of senescence exhibited by each cultivar.

Carbon partitioning among aboveground plant parts was very similar to that for biomass (Fig. 2). Differences among cultivars, years, and their interaction with sampling date were present for some, but not all plant components (Table 2). Total C stored in biomass at the final harvest averaged 372 g m^{-2} yr^{-1} for Sunburst and 259 g m^{-2} yr^{-1} for Dacotah (Fig. 2). Stems contained the most biomass C at final harvest in Sunburst, but in Dacotah senesced biomass had more biomass C. Total biomass C in plant components varied between cultivars: Sunburst stems contained 47% and Dacotah stems 41%, Sunburst senesced biomass contained 38% and Dacotah 49%, Sunburst leaves contained 12% and Dacotah leaves 5%, and Sunburst litter contained 4% and Dacotah 5%. The greater amount of senesced biomass C for Dacotah reflects the earlier maturity of Dacotah compared to Sunburst.

Root biomass in the top 0.3 m of soil accounted for 49% of total root biomass for Dacotah and 46% for Sunburst (Fig. 3). Root biomass for both cultivars gradually declined with increasing depth. Root biomass was not different among cultivars, but years differed. Total root biomass was statistically similar in 2000 (6540 kg ha^{-1}) and 2001 (5950 kg ha^{-1}), but greater in 2002 (7670 kg ha^{-1}) than the previous 2 yr (Table 3). These root biomass totals were similar to the 7236 kg ha^{-1} root biomass in switchgrass grown in eastern Canada (Zan et al., 1997), but much lower than the 14.4 Mg ha^{-1} in a native mixed-grass prairie (Frank and Dugas, 2001). Root:shoot ratios were statistically different among years (Table 3), but differences were not present among cultivars nor was the cultivar by year interaction significant. Root:shoot ratios were greatest in 2000 (0.35) and 2002 (0.36), and the ratio in 2002 was statistically greater than in 2001 (0.27) (Table 3). These root:shoot ratios were less than half of those reported by Davidson (1969) for cool-season grasses. The removal of crown tissue from the root biomass totals reduced the root:shoot ratios.

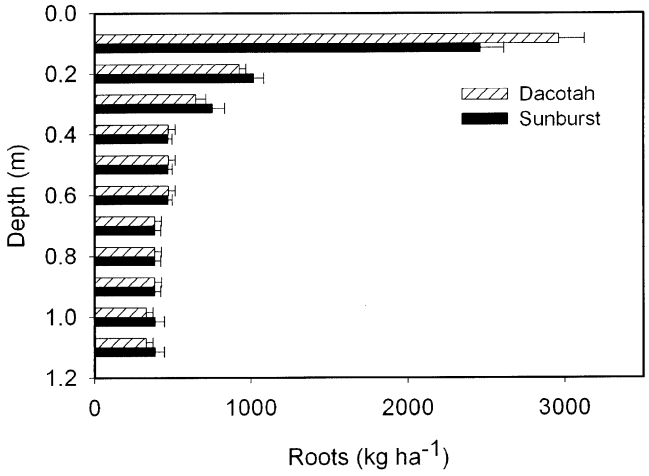

Fig. 3. Root biomass in increments to 1.1-m depth for Dacotah and Sunburst switch sampled in 2000, 2001, and 2002. Data for increments 0.3 to 0.6 m, 0.6 to 0.9 m, and 0.9 to 1.1 m were partitioned into 0.1 m increments to better illustrate trends in root biomass with soil depth. Horizontal bars are standard errors of the mean.

Soil CO_2 fluxes increased rapidly from early May until mid-July and then decreased rapidly until late October during each year (Fig. 4). Soil CO_2 flux over time, coincided with changes in soil temperature as shown by others (Frank et al., 2002; Mielnick and Dugas, 2000). Peak soil CO_2 fluxes were lower during the drought year of 2002 compared to the above average precipitation years of 2000 and 2001. Total soil respiratory CO_2 losses during the growing period trended higher (not significantly) each year for plots of Dacotah compared to Sunburst. Differences between cultivars and the cultivar × year interaction were not significant, but year effects were significantly different. Soil CO_2 losses measured every 15 to 21 d and scaled for the period from early May to late October were significantly greater in 2000 (−533 g CO_2 – C m^{-2}) and 2001 (−509 g CO_2 – C m^{-2}) than during the drought year of 2002 (−452 g CO_2 – C m^{-2}) (Table 4). Average soil C loss was −498 g CO_2 – C m^{-2} for the 1 May to 17 October period over the 3 yr in this study.

Soil organic C to 0.9-m depth increased in a linear fashion from baseline soil C content in 1999 through 2002 ($r^2 = 0.99$) (Fig. 5). Year effects were significant, but cultivars and the cultivar × year interaction were not significant. Changes in soil C were greater at sample depths from 0.3 to 0.9 m than from 0 to 0.3 m. Regression analysis indicated soil organic C to 0.9-m depth increased at the rate of 1.01 kg C m^{-2} yr^{-1}. As a comparison, soil C content averaged across cultivars and sites

Table 3. Aboveground biomass, root biomass, and root:aboveground biomass ratio for Dacotah and Sunburst switchgrass in 2000, 2001, and 2002. Crown biomass was included in aboveground biomass.

Year	Aboveground	Roots	Ratio
	kg ha^{-2}		
2000	20 150a†	6 540a	0.35ab
2001	23 690a	5 950a	0.27a
2002	22 620a	7 670b	0.36b

† Columns with different letters are significantly different at $P = 0.01$.

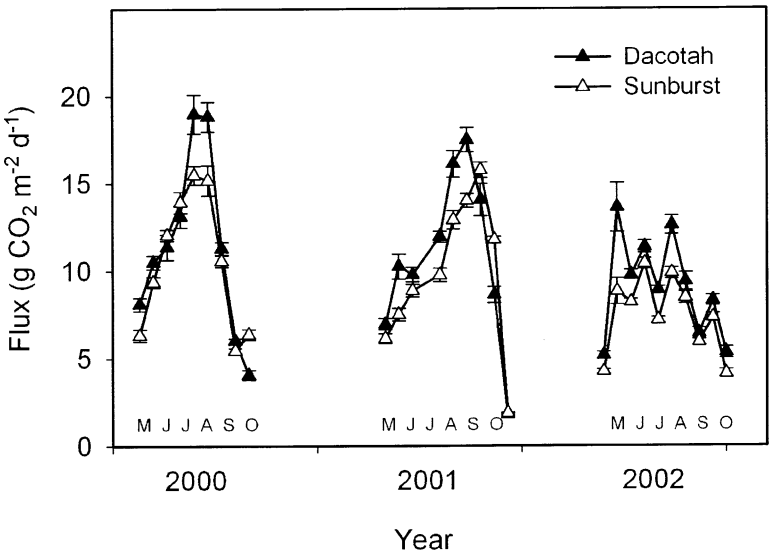

Fig. 4. Soil CO_2 flux for Dacotah and Sunburst switchgrass on 10 dates in 2000, nine dates in 2001, and 11 dates in 2002. Measurements were made from early May to late October as indicated by the first letter of the month above the *x* axis. Vertical bars are standard errors of the mean.

was 7.2 kg C m^{-2} to 0.3-m depth, whereas a native grassland pasture and a continuous cropped wheat site on the same soil series as the south site contained 8.7 and 5.9 kg C m^{-2}, respectively (unpublished data). Mensah et al. (2003) measured gains in soil organic C on reseeded grasslands in east central Saskatchewan, Canada (approximately 53°N, 105°W) of 0.07 Mg C ha^{-1} yr^{-1} (equal to 0.5 kg C m^{-2} to 0.9-m depth) from sites that had been restored for 5 to 12 yr. In analyzing for soil C, the two sites were treated as a random effect in the statistical model, so no *F*-test was generated. The Wald test was performed, however, for the variance of the random effect of site. This was significant at the 0.0086 level, which suggests that variability of soil C due to sites was significantly greater than zero.

Allocation of C in plant biomass, soil C loss through respiration, and C gain were significant primarily for year effects (Table 4). Carbon captured in aboveground vegetation decreased over years. During the drought year of 2002, aboveground biomass C was reduced 65% compared with 2000 and 72% compared with 2001. In contrast to aboveground vegetation, crown biomass C increased as the plants increased in age over years and was 200% greater in 2002 compared to 2001. Crown tissue C content was greatest in the drought year of 2002, which may be partly caused by drought-induced C storage in this carbohydrate storage organ and partly to increased plant age. The greater biomass C in the drought year of 2002 reflects the plants partitioning of carbohydrate reserves to storage organs during stressful periods (Davidson, 1969). Morgan et al. (2001) also showed that nitrogen stress caused perennial cool-season grasses to partition more carbohydrates to belowground organs. Although not significant, Dacotah crown tissue on average contained 17% more C than Sunburst for all years. Root biomass C also increased by 140% from 2000 to 2002. Although cultivars were not different, the trend showed Dacotah to have greater root C than Sunburst. The 3 yr average root C content was only 50% of crown biomass C. The partitioning of C among components of plant biomass showed aboveground vegetation contained 18%, crown tissue 55%, and roots 27% of total biomass C.

Table 4. Carbon in aboveground, crown, and root plant biomass, C loss from soil respiration, and calculated C gain in switchgrass cultivars Dacotah and Sunburst from 1 May to 17 October over 3 yr at Mandan, ND. Year effects were significant for aboveground, crowns, roots, and soil CO_2 fluxes, but not for cultivar or the year × cultivar interaction.

Year	Aboveground biomass†	Crown biomass	Root biomass	Soil CO_2 flux‡	Carbon gain
	g C m^{-2}			g CO_2–C m^{-2}	g C m^{-2}
2000	365b§	457a	272a	−533a	561
2001	457c	492a	273a	−509a	713
2002	126a	935b	390b	−452b	999
Avg.	316	628	312	−498	758

† Aboveground biomass includes all green and senesced plant parts.
‡ Soil CO_2 flux is the average of flux measurements every 15 to 21 d from early May to late October times the days during that period.
§ Columns with different letters are significantly different at $P = 0.01$ except crowns at $P = 0.08$.

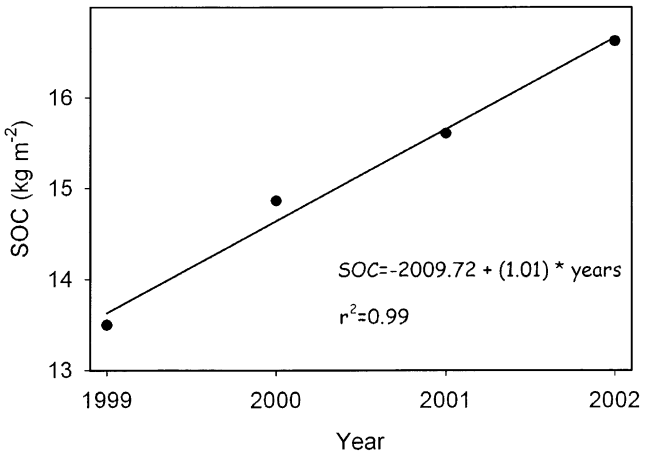

Fig. 5. Total soil organic carbon content to 0.9-m soil depth for switchgrass in 2000, 2001, and 2002. The *F*-test evaluated by SAS PROC MIXED model was significant for years at the 0.05 level, but nonsignificant for cultivars and cultivars × years.

Net system C gain (biomass C − soil CO_2 flux during 1 May–17 October) increased over the 3 yr after seeding. Total C gain nearly doubled from 2000 to 2002. The increase in C gained coincided mostly with the increase in crown biomass C. Average C gain over the 3 yr was 758 g C m^{-2}. The quantity of C lost from the soil, mainly through respiration processes, was equal to 40% of the biomass C in aboveground vegetation, crown, and root biomass for both cultivars. Although not measured, soil respiratory losses during the dormant period (18 October–31 April) could be expected to somewhat reduce net C gain.

Overall there were few differences among the two cultivars evaluated in this study. Root biomass averaged only 26% of the total plant biomass in Dacotah and 28% in Sunburst when crown tissue was included with aboveground biomass, and 84% in Dacotah and 80% in Sunburst when crown tissue was considered root biomass. Carbon partitioning among aboveground, crown, and root biomass showed that crown tissue contained approximately 50% of the total biomass C. Although an amount equal to nearly half of the biomass C captured during a year was lost through soil respiratory processes, the quantity of C gain measured in the soil indicated that switchgrass has potential for storing a significant quantity of soil C in the northern Great Plains.

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